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(54) Measurement of distance using ultrasound

(57) Distance measuring apparatus comprises a carrier signal generator (5), an audio-frequency modulation signal generator (6, 8, 9) to generate a modulation signal having a frequency f, and a modulator (3) to frequency-modulate the carrier signal with the modulation signal. A transmitting transducer (1) is energizable by the frequency-modulated carrier signal to transmit ultrasound energy. A receiving transducer (2) is spaced from the first point by a distance which is to be measured, and receives at least part of the transmitted ultrasound energy. A phase comparator (11) monitors the phase relationship between the audio modulation received by the receiving transducer and the transmitted audio modulation, to give a first indication (14) of the measured distance. The modulation frequency can be changed, so that finer indications (16, 18) of the distance are provided. The modulation signal generator comprises transmitting and receiving transducers (6, 8) spaced apart by a reference distance (7) and a phase-lock loop (9) to adjust the generator frequency to maintain a constant phase relationship between the transmitted and received modulation signals.

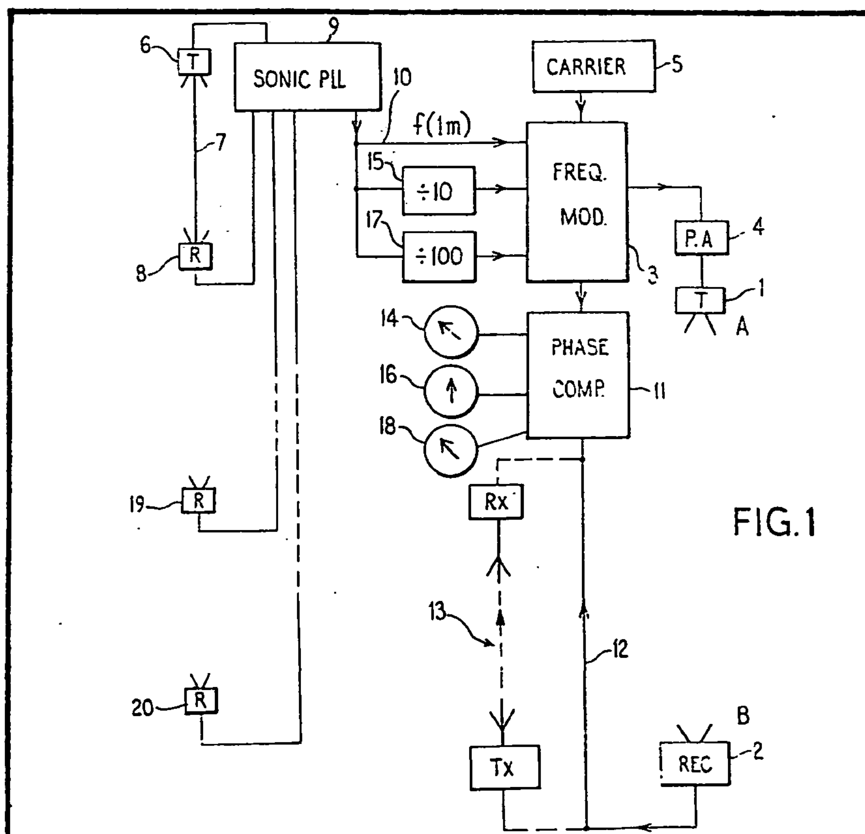

FIG.1

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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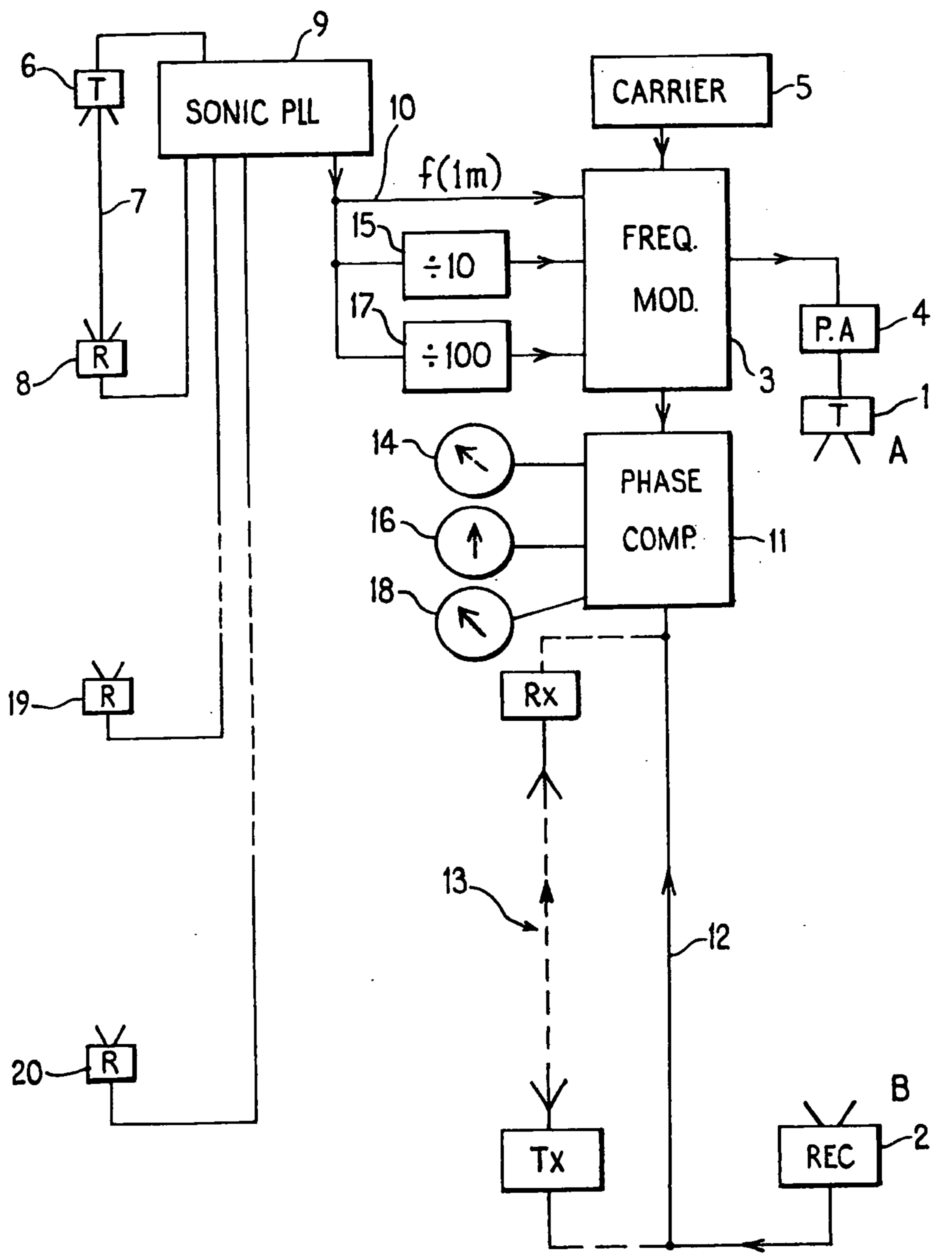
SONIC PLL
9
6
T
7
8
R
10
f(1m)
CARRIER
5
FREQ.
MOD.
3
15
÷10
17
÷100
P.A
4
T
1
A
14
16
18
PHASE
COMP.
11
19
R
Rx
13
12
20
R
Tx
REC
2
B

FIG.1

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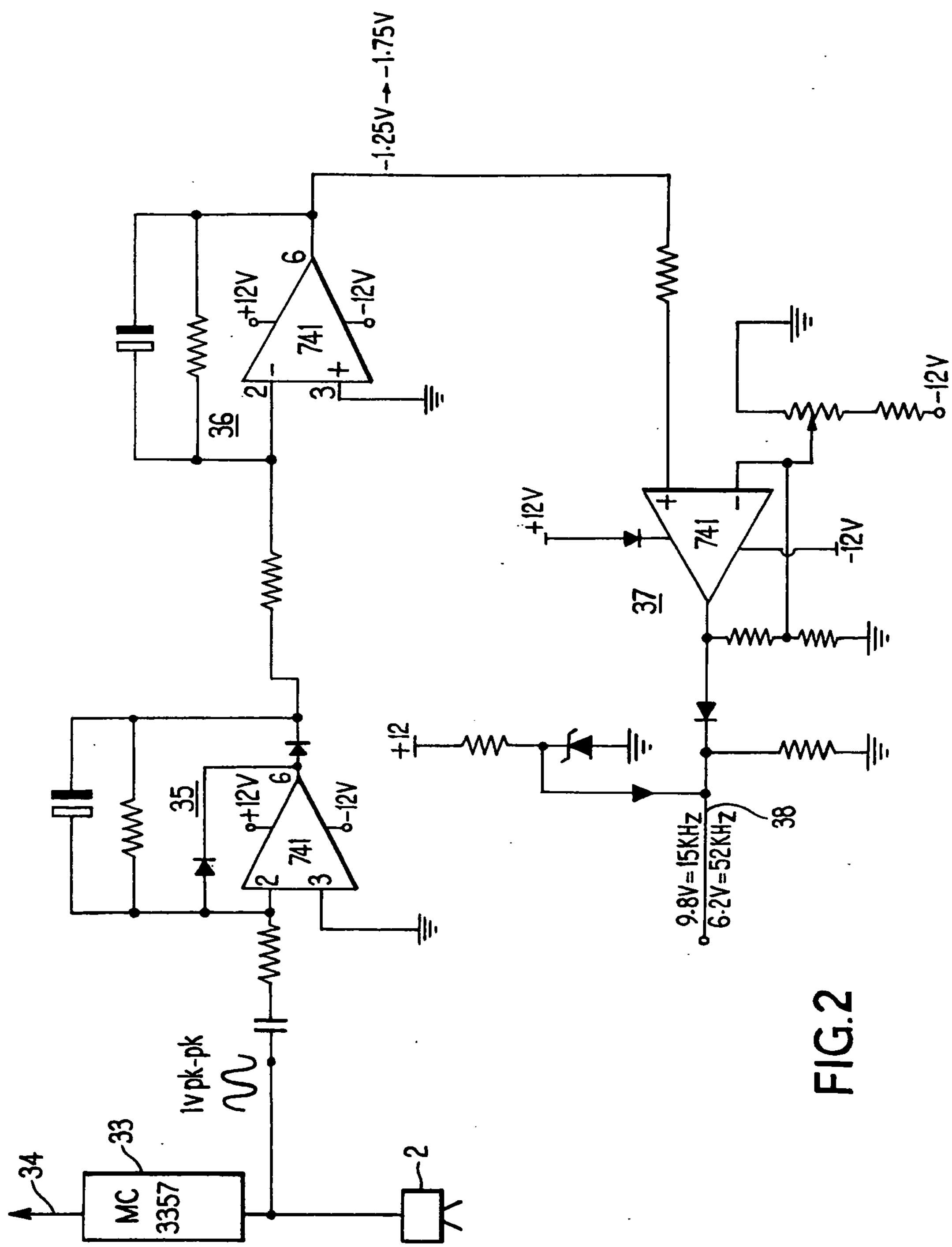

FIG.2

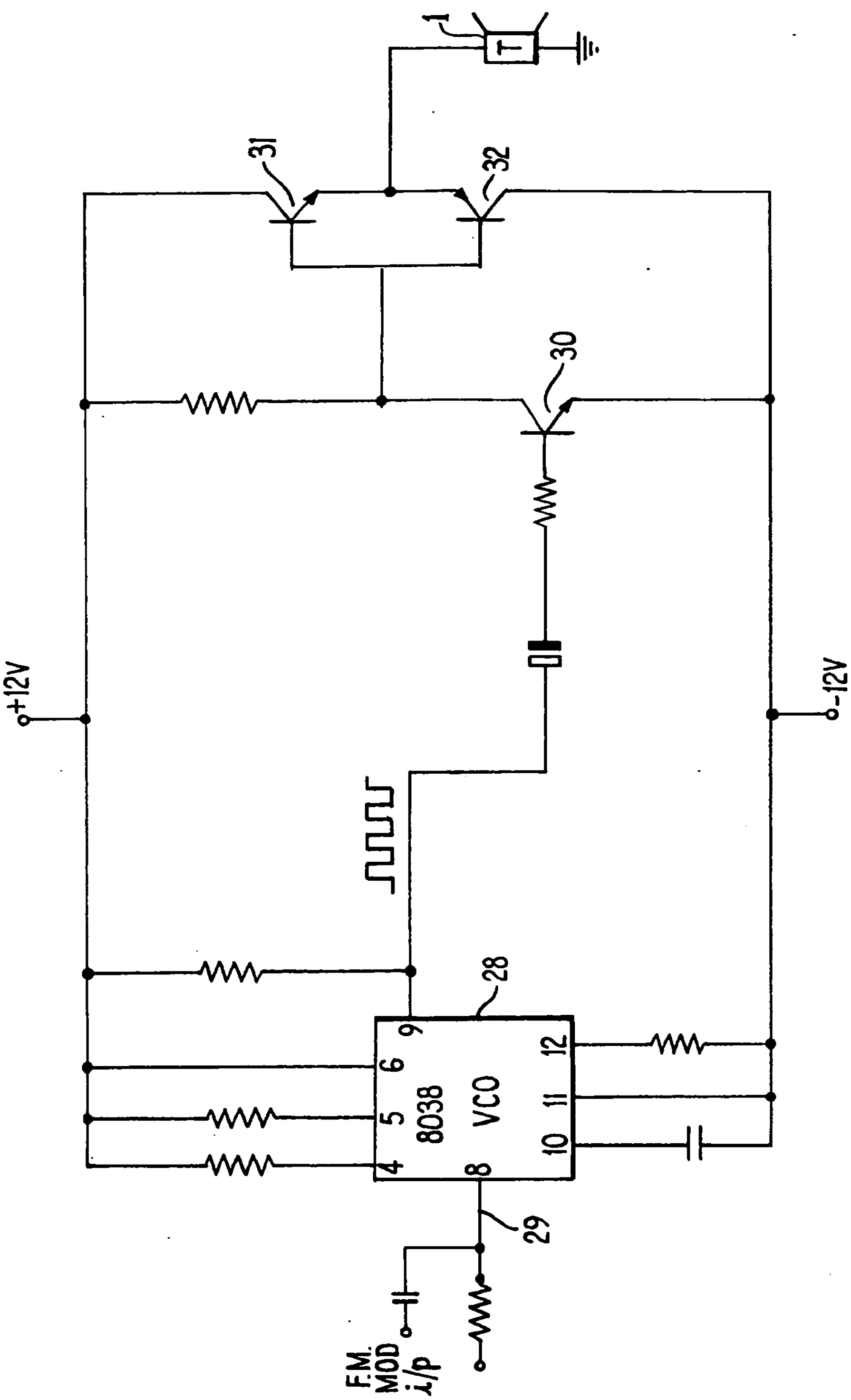

FIG.3

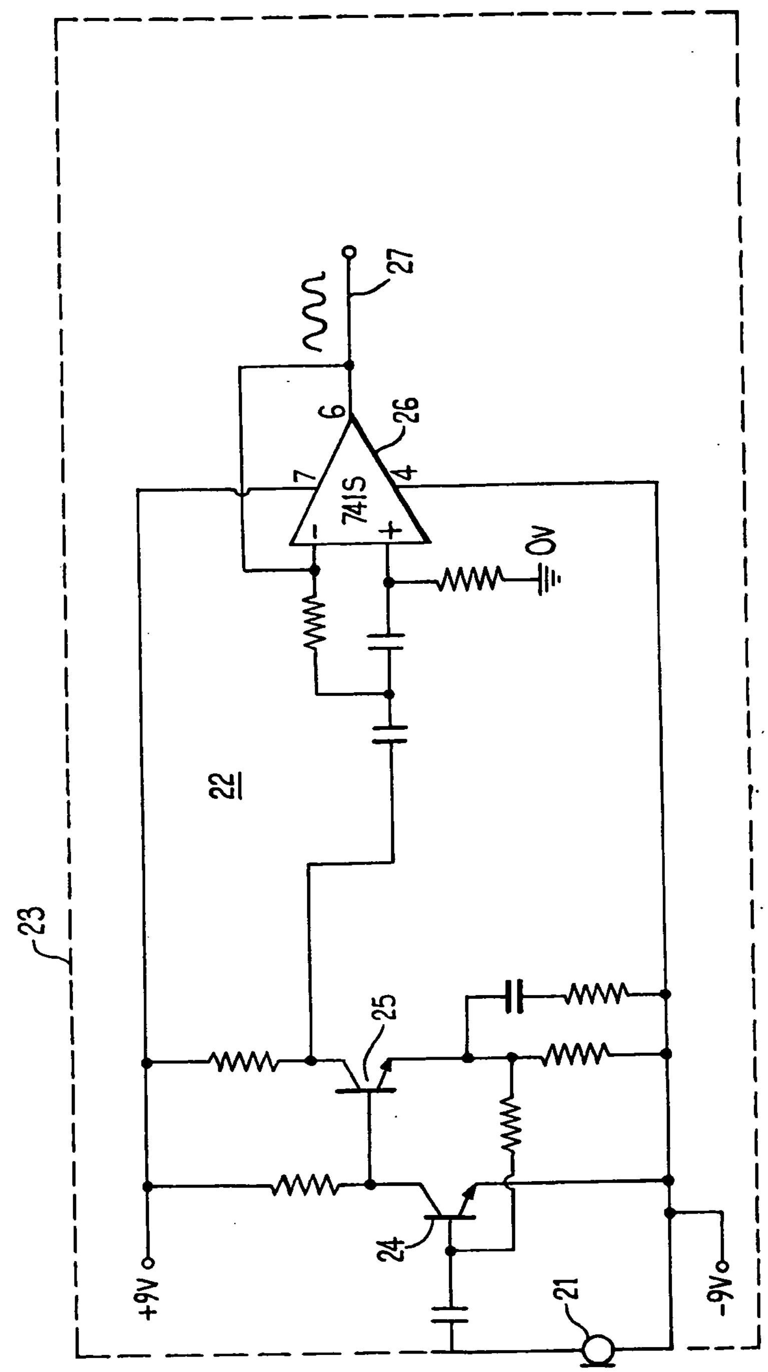

FIG.4

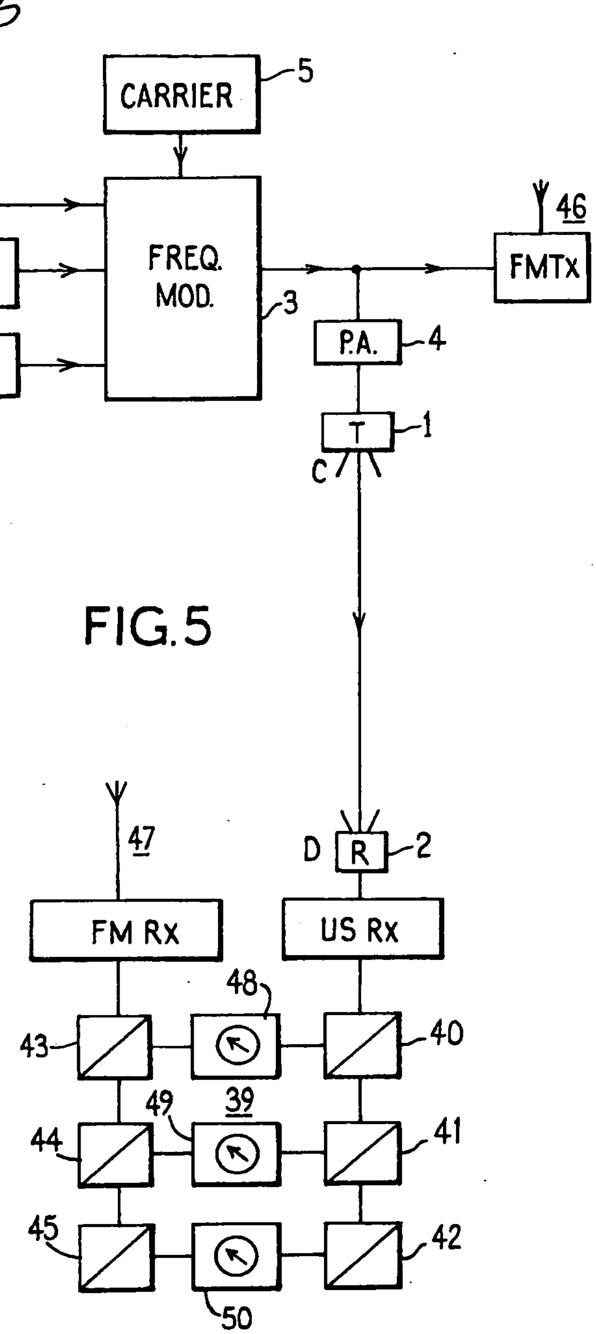
SONIC P. LL
9
6
T
8
R
19
R
20
R
f(1m)
15
÷10
17
÷100
CARRIER
5
FREQ. MOD.
3
FMTx
46
P.A.
4
T
1
C
D
R
2
47
FM Rx
US Rx
48
43
40
49
39
44
41
45
42
50

FIG.5

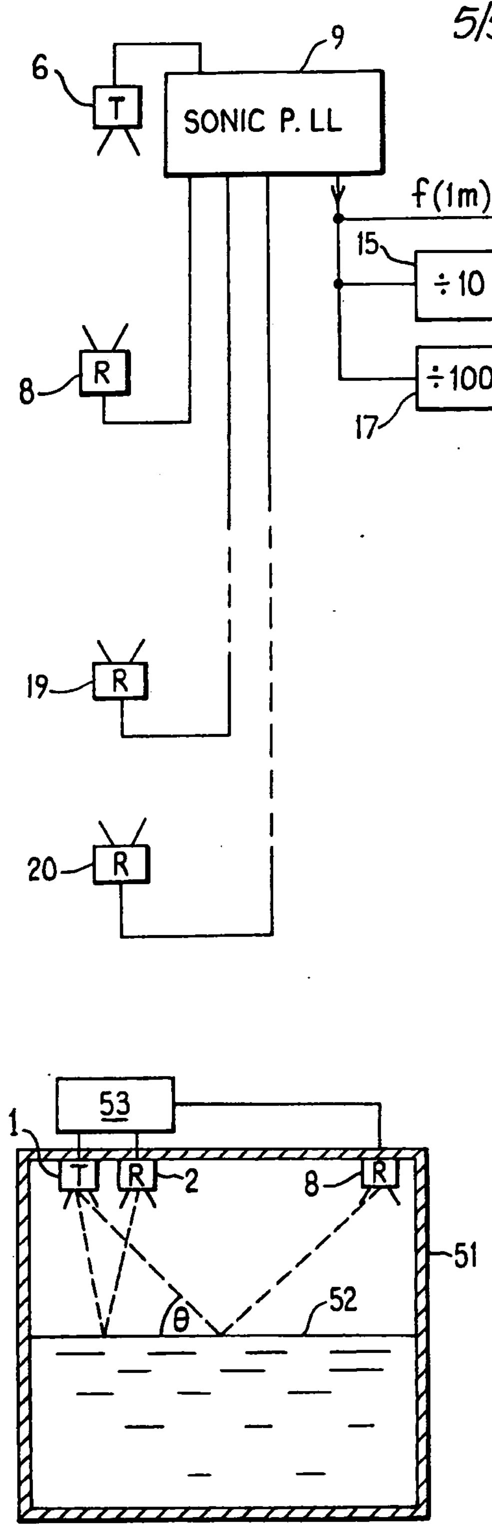
53
1
T
R
2
8
R
51
52
θ

FIG.6

SPECIFICATION

Measurement of distance using ultrasound

This invention relates to apparatus for the measurement of distance using ultrasound.

The use of ultrasound is well-known for detection and ranging, and particularly for determining the depth of the ocean or the position of a shoal of fish or a submarine. Conventional systems employ the emission of a sharp pulse and measurement of the delay until an echo is received back at the sending point. When such a system is used in air, the range is very much reduced, since the attenuation of the air is greater than that of water and, in consequence, the frequency has to be reduced to just above the audio range. This, in turn, limits the accuracy with which a wave front can be detected and, in practice, ultrasound is useful only for distances between, say, 1m and 100m in air. For measurements over short distances, magnetic and proximity devices are well established, whereas above 100m it is usually more convenient to use light and radio beams.

For ranges of around 10m in air, ultrasound has considerable merit, in that it is non-intrusive and cheap, and has few physiological side-effects and is thus superior to electro-magnetic radiation in some circumstances.

Apparatus for measuring distance using ultrasound by a method which is far superior to pulse emission is disclosed in my British Patent No. 2,043,899. In that method, an ultrasound carrier signal, frequency-modulated by an audio-frequency signal, is fed to a transducer, and resulting ultrasound energy is received at a second transducer. The phase of the received modulation is compared with the phase of the transmitted modulation, and an indication of distance is derived from the phase relationship.

It is an object of the present invention to provide such an apparatus in which both coarse and fine measurements of a distance are produced.

According to the present invention, distance measuring apparatus comprises means to generate an electric carrier signal; means to generate an audio-frequency modulation signal having a frequency f; modulator means to frequency modulate the carrier signal with the modulation signal; a first transducer located at a first point and energizable by the frequency-modulated carrier signal to transmit ultrasound energy; a second transducer located at a second point spaced from the first point by a distance which is to be measured, the second transducer being arranged to receive at least part of the transmitted ultrasound energy; means responsive to the phase relationship between the audio modulation received by the second transducer and the audio modulation transmitted by the first transducer to give a first indication of said distance; and means operable to change the modulation signal frequency to a second frequency f/n, where n is a positive integer, whereby a finer second indication of said distance is provided by said phase relationship responsive means.

The measurement of distance using ultrasound suffers from one major drawback, namely that the transmission of sound is dependent upon the medium as regards velocity and attenuation, and these change with the ambient conditions. For example, the speed of sound in air is 331.46 m/s for dry air at 0°C, and changes by 0.607 m/s per °C. There are also minor changes with humidity and pressure and variations in carbon dioxide content. Some form of compensation for the speed of sound is therefore necessary in many cases.

One obvious way of compensating is to measure the temperature and to allow for its variations in the time/distance conversion factor. This is, however, only approximate, since the temperature will be read at one point only.

A better method is to use a comparator technique involving a reference distance, as often adopted in pulse-echo system. A small target, often in the form of a pin, fixed a short distance in front of the sensor is employed to give a reading representing a known reference distance. However, the reference distance in practical circumstances must be shorter than the working range; in measuring the depth of a liquid in a tank it is usually limited to the dead space above the high level mark. Consequently, as the level falls, the reference becomes a decreasing fraction of the measured path and any variations beyond the reference distance will not be compensated. Since the temperature and vapour content adjacent to the liquid may well be different from that near the datum, the compensation depends on the extent to which the reference distance conditions represent the actual path. This imposes a basic limitation on the finite accuracy capability of the system.

In the case of pulse echo systems, and particularly in systems in which the same transducer is used for transmission and reception of pulses, there seems little that can be done to make a short reference distance more representative of the ambient conditions. It appears, at first sight, that a continuous wave system can be improved by pointing a reference transducer downwards to recieve reflections from the surface of the liquid so that a bigger part of the total path is traversed by both beams. However, there seems inherently to be no advantage, since the reference is still the short distance in the dead volume at the top of the tank.

A preferred embodiment of the present invention, by means of which the depth of a liquid is measured, provides improved compensation for the ambient conditions.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 is a block schematic diagram of a first form of distance measuring apparatus in accordance with the invention,

Figs. 2 and 3 together form a block schematic diagram of a carrier signal control circuit and a transmitter circuit of the apparatus of Fig. 1,

Fig. 4 is a block schematic diagram of a preamplifier and filter circuit for use with a particular type of receiving transducer in the circuit of Figs. 2 and 3,

Fig. 5 is a block schematic diagram of an alternative distance measuring apparatus in accordance with the invention, and

Fig. 6 is a block schematic diagram of a liquid level measuring apparatus in accordance with the invention.

Referring to Fig. 1 of the drawings, apparatus for measuring the distance between two points A and B comprises a transmitting transducer 1 located at the point A and a receiving transducer located at the point B. The transducer 1 is fed with a frequency-modulated carrier signal from a modulator 3, via a power amplifier 4. The carrier signal is provided by a circuit 5, which will be described in detail later.

In order to determine a suitable modulation frequency, a reference transmitting transducer 6 transmits over a reference distance 7 through the atmosphere in which the measurement is to be made. The reference distance 7 may, for example, be 1 metre. The transmitted wave is received by a receiving transducer 8, and a phase-lock loop 9, to which the transducers 6 and 8 are connected, sets the frequency f of the transmitted wave such that it is resonant for the selected reference distance in the prevailing ambient conditions.

The signal at the frequency f set by the phase-lock loop 9 is fed to the modulator 3 over a line 10, to act as the modulating frequency.

The frequency-modulated carrier signal fed to the transducer 1 causes the transducer to transmit a frequency-modulated ultrasound wave, at least part of which is received by the receiving transducer 2. The signal from the transducer 2 is fed to a phase comparator 11 via a wire link 12 or a radio link 13.

The phase of the received modulation is compared with the phase of the transmitted modulation by the comparator 11, and the phase relationship gives a measure of the distance AB as compared with the reference distance 7. The distance is indicated on a meter 14 which is connected to the comparator. However, this meter can only indicate the phase displacement of one cycle of the received modulation; it cannot indicate the number of complete wavelengths between the points A and B. If, now, the frequency f is divided by 10 in a divider circuit 15, and the resulting frequency is used to modulate the carrier, a different phase relationship will result, and this will be indicated on a corresponding meter 16, giving a finer distance measurement. The frequency f is also divided by 100 in a divider circuit 17, and a further indication is given on a meter 18. It is not essential to use ÷10 and ÷100 circuits; other divisors could be used, depending upon, for example, the maximum range of distances envisaged.

Instead of dividing the basic reference frequency f, using dividers 15 and 17, separate reference transducers 19 and 20 spaced 10 times and 100 times as far from the transmitting transducer 6 as the transducer 8 could be used. The resulting resonant frequencies set up by the phase-lock loop 9 would be substantially f/10 and f/100, respectively, but this would, in fact, improve the performance of the apparatus because the references would be more representative of any non-uniformities within the path. If the reference is longer than the path over which the measurement is being made, then the compensation for temperature and other velocity effects is virtually complete, since the performance is only related to the sensitivity of the system. Because the system is fully electronic, errors due to deadzones and hysteresis are eliminated. The main limitations on the performance are a function of the noise in the received signal due to random variations. In this connection it is worth noting that the continuous wave system is far superior to the pulse-echo type of operation because the latter provides periodic results following pulsing of the system for short intervals of time, whereas the present system, in which continuous monitoring of phase is carried out, gives a result which follows all the random and ambient changes occurring in the measurement path. A pulse system will give a number of spot readings, and even if many readings are taken and averaged the result could still be inaccurate due to "aliasing". On the other hand, the present continuous system shows a reading on a meter which endeavours to follow all of the excursions. If the indicating device is a pointer and dial instrument with suitable damping, it is easy to judge the noise in the system at all times and to estimate visually the average figure.

The apparatus is very versatile and can be adapted to circumstances. For example, one carrier signal could carry at least three measuring waves as modulation, their separation being achieved by filters at the receiving end, or the measuring waves could be sent as three separate modulated carrier signals of different frequencies. In fact, these carrier frequencies could be at variable or fixed values which are suitable for the distances at which it is required to receive the particular wave.

The carrier frequency is in no way critical to the operation of the sonic phase-locked loop. The carrier is chosen to suit the characteristics of the transducer, while being high enough to ensure that there is adequate attenuation in the path to enhance the well-known FM single-signal capture effect. For measurement purposes, the ideal carrier frequency is the highest one at which a just-limiting signal is received by the receiving transducer, since this means that the path has minimum energy input and minimum disturbance. However, this requires the use of broadband transducers, whereas most piezo-ceramic units and crystals are resonant. Fortunately, in the area

where the present invention is especially applicable, namely for distance measurement in a range of 1—100m in air, the carrier wave has to be below about 50kHz, and audio devices are available which will operate satisfactorily at such frequencies. In particular, the tweeter loud speaker and the electret microphone are capable of operation well above the audio range. As an example, a miniature microphone as used in hearing aids can operate up to about 160kHz, and it is usually necessary to cut the response deliberately in an amplifier which is fed by the microphone.

A circuit for use with such a microphone is shown in Fig. 4 of the drawings. In that figure, the microphone 21 is connected to the input of an amplifier and filter circuit 22, preferably contained within a screening box 23. The amplifier section of the circuit comprises transistors 24 and 25 and associated components connected in a conventional circuit. The filter section comprises an operational amplifier 26 and associated components arranged to give, for example, a roll-off characteristic below 10kHz. The output of the circuit is fed to a line 27 for connection to the circuit of Fig. 2.

An alternative to such microphone and filter combination is a sonic transducer of the wide band non-resonant type comprising a metalised film caused to vibrate by capacitive electro-static action. However, such transducers require a polarising voltage. In certain models, for example the AKG 3020 unit, the response is naturally quite poor below about 15kHz but is adequately linear up to at least 60kHz.

As mentioned previously, the carrier frequency is selected such that it is the highest frequency which gives an adequate signal along the measurement path. This selection is achieved by the circuitry shown in Figs. 2 and 3.

Referring, firstly, to Fig. 3, the carrier signal is generated by a voltage-controlled oscillator 28 which produces a pulse train having a repetition frequency which is dependent upon the voltage applied to an input 29. The pulse train is fed to an amplifying transistor 30 and thence via a power amplifier comprising complementary transistors 31 and 32 to the transmitting transducer 1.

Referring to Fig. 2, the resultant ultrasound energy reaches the receiving transducer 2. That transducer may comprise the whole of the circuit of Fig. 4 as described above, or may be any other suitable transducer. The carrier signal is fed to an IF and demodulator circuit 33 which outputs the modulation signal on a line 34 for phase comparison with the transmitted modulation as explained above. The carrier is also fed to an AC/DC converter 35 which determines the average value of the carrier amplitude and feeds a signal representing that value to an integrator 36 having a long time constant. The output of the integrator is a voltage varying from −1.25 volts to −1.75 volts depending upon the frequency of the carrier signal. That voltage is fed to an offset-determining circuit 37 which can be adjusted to set the upper and lower limits of the resultant frequency control voltage which it feeds to a line 38 and thence to the control input 29 of the oscillator 28. With the particular oscillator used, an upper limit control voltage of 9.8 volts produces a frequency of 15kHz and a lower limit voltage produces a frequency of 52kHz.

When the apparatus is in use, the integrator will gradually increase the negative voltage, thereby reducing the VCO control voltage. The carrier frequency will therefore increase, and this will continue until such time as the attenuation in the ultrasound path causes a reduction in the amplitude of the received carrier at the input of the converter 35. The control voltage then increases, thereby reducing the carrier frequency. The carrier frequency therefore sets at the highest level which will produce an adequate signal at the converter 35, despite the attenuation in the path.

The modulation signal is fed to the control input 29 of the VCO 28 from the phase-lock loop 9 or from the divider 15 or 17 of Fig. 1, as the case may be.

An alternative arrangement is shown in Fig. 5 in which the same components as used in Fig. 1 have the same reference numerals. In this case, the receiving transducer 2 is contained in a portable unit 39, which also contains audio filters 40—42 for separating the three modulation frequencies (f, f/10, f/100), and phase comparators 43—45. The transmitted modulation is also fed over an FM radio link 46, 47 to the phase comparators 43—45 for comparison with the received modulation phase. The phase relationships, and hence the distance measurements, are indicated on meters 48—50.

The transmitter can therefore act as a beacon at a location C, and the portable unit 39 can be pointed at the beacon whilst held at any location D within range of the beacon. The distance CD can then be read off. Again, the frequency dividers may be dispensed with and further reference transducers 19 and 20 used as in Fig. 1.

Two such systems could be employed with the two transmitting transducers pointing in mutually perpendicular directions and located at the centres of adjacent sides of a square. A portable receiver unit could then determine its exact position within the square. Such a system could be used for controlling the position of a robot.

Three-dimensional operation would also be possible by employing three transmitter systems in which the transducers face in mutually perpendicular directions. To avoid ambiguity, the three systems could have different carrier frequencies so that each axis could be tuned-in in turn at the receiving point, or three receivers could be used.

Although the above embodiments have been described in relation to air, the apparatus could also be used in any sound transmitting medium. For example, it could be used in water, for navigation or for the control of diving.

Fig. 6 illustrates the use of apparatus in accordance with the invention for determining

the depth of liquid in a tank 51 by measuring the distance between the surface 52 of the liquid and the top of the tank. In this case, the transducers 1 and 2 are located at the top of the tank pointing downwards, and the transducer 2 receives the ultrasonic beam after reflection from the surface of the liquid. The result of the measurement is, therefore, always twice the actual distance which is being measured. The components 3, 4, 5, 9, 10, 11 and 14 (and 15—18, if required) of Fig. 1 are contained in a unit 53. The reference receiving transducer 8 is located at the top of the tank, displaced from the transducer 1 by a reference distance which is as large as convenient. In this embodiment the transducer 8 also receives its signal from the transducer 1 instead of a separate transmitting transducer being used for the reference path. The respective transit times from the transmitting transducer 1 to the surface 52 and thence to the two receiving transducers 2 and 8 are measured. The difference between these two times varies as the sine of the angle θ between the second beam path and the surface, because of the displacement of the second transducer by the reference distance. This appears to give complete compensation for ambient conditions, provided that any temperature or vapour concentration gradients are uniform, which seems very likely in the case of an air space.

This triangulation method of compensation in which the reference receiving transducer is spaced an appreciable horizontal distance from the transmitting transducer is far better than the conventional target-pin method mentioned above.

The type of apparatus used in the Fig. 6 embodiment, in which the transducers all face towards a surface so that the receiving transducers receive ultrasound transmissions after reflection from the surface, and in which the reference distance is measured along the plane in which the transducers are located, may be used for other measurements besides the measurement of liquid level in a tank.

Claims

1. Distance measuring apparatus, comprising means to generate an electric carrier signal; means to generate an audio-frequency modulation signal having a frequency f; modulator means to frequency modulate the carrier signal with the modulation signal; a first transducer located at a first point and energizable by the frequency-modulated carrier signal to transmit ultrasound energy; a second transducer located at a second point spaced from the first point by a distance which is to be measured, the second transducer being arranged to receive at least part of the transmitted ultrasound energy; means responsive to the phase relationship between the audio modulation received by the second transducer and the audio modulation transmitted by the first transducer to give a first indication of said distance; and means operable to change the modulation signal frequency to a second frequency f/n, where n is a positive integer, whereby a finer second indication of said distance is provided by said phase relationship responsive means.

2. Apparatus as claimed in Claim 1, wherein the means operable to change the modulation signal frequency is further operable to change that frequency to f/m, where m is a positive integer larger than n, whereby a third indication, finer than said second indication, is provided by the phase relationship responsive means.

3. Apparatus as claimed in Claim 1 or Claim 2, further comprising a first reference receiving transducer spaced by a reference distance from a reference transmitting transducer, the reference transducers being connected in a phase-lock loop circuit which sets the modulation frequency f in dependence upon the reference distance and the ambient conditions in the path between the reference transducers.

4. Apparatus as claimed in Claim 3, further comprising a second reference receiving transducer spaced from the reference transmitting transducer by a distance n times the reference distance of said first reference receiving transducer, whereby the phase-lock loop can set the modulation frequency at f/n.

5. Apparatus as claimed in Claim 4, further comprising a third reference receiving transducer spaced from the reference transmitting transducer by a distance m times the reference distance of said first reference receiving transducer, m being a positive integer larger than n, whereby the phase-lock loop can set the modulation frequency at f/m.

6. Apparatus as claimed in any preceding claim, further comprising a radio link between the second transducer and the phase relationship responsive means for communicating to said responsive means the phase of the received audio modulation.

7. Apparatus as claimed in any one of Claims 1—5, further comprising a radio link between the modulator means and the phase relationship responsive means for communicating to said responsive means the phase of the transmitted audio modulation.

8. Apparatus as claimed in any preceding claim, further comprising means to set the frequency of the carrier signal as high as is compatible with reception of an adequate signal by said second transducer.

9. Apparatus as claimed in Claim 3, wherein said first transducer acts also as said reference transmitting transducer; wherein said first transducer, said second transducer and said first reference receiving transducer are all located substantially in the same plane and point towards a surface the position of which is to be measured; and wherein said reference distance between said first reference receiving transducer and said first

transducer is measured along said plane.

10. Apparatus as claimed in Claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

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